NEUTRINOS AS SOURCE OF ULTRA HIGH ENERGY COSMIC RAYS IN EXTRA DIMENSIONS

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Abstract

If the neutrinos are to be identified with the primary source of ultra-high energy cosmic rays(UHECR), their interaction on relic neutrinos is of great importance in understanding their long intergalactic journey. In theories with large compact dimensions, the exchange of a tower of massive spin-2 gravitons (Kaluza-Klein excitations) gives extra contribution to $\nu\bar{\nu} \longrightarrow f\bar{f}$ and $\gamma\gamma$ processes along with the opening of a new channel for the neutrinos to annihilate with the relic cosmic neutrino background $\nu\bar{\nu} \longrightarrow G_{kk}$ to produce bulk gravitons in the extra dimensions. This will affect their attenuation. We compute the contribution of these Kaluza-Klein excitations to the above processes and find that for parameters of the theory constrained by supernova cooling, the contribution does indeed become the dominant contribution above $\sqrt{s} \simeq 300 GeV$.

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Ultra high energy (UHE) cosmic rays [1] present a challange in cosmology and astroparticle physics. Energies beyond the Greisen-Zatsepin-Kuzmin (GZK) cut off $\sim 5 \times 10^{19}$ eV excludes protons as primary candidates [2] for high energy events due to the fact that above the resonance threshold for Δ^* production, the protons would lose roughly 20 % of their energy by scattering on the 2.73 K cosmic background photons through $p + \gamma_{2.73K} \longrightarrow \Delta^* \longrightarrow N + \pi$ during 6 Mpc (mean free path) of their journey. Thus apart from the difficulty in accelerating particles to such extremely high energies [3], these protons would lose significant fraction of their energy if they came from 100 Mpc or further away. Gamma rays and neutrinos could be other primary candidates which will not be hampered by the GZK cut off. The high energy photon annihilation cross-section on cosmic background photons [4] will however, preclude them from being the candidates particularly if they have to travel a distance of the order of 100 Mpc of the intergalactic space, their mean free path being of the order of 10-40 Mpc only. Weiler [5] proposed that if neutrinos have to be the source of UHE cosmic rays, they have to have their energies corresponding to the Z-resonance in order to be able to effeciently annihilate relic neutrinos i.e. $E_\nu \simeq \frac{M_Z{}^2}{2M_\nu} \simeq 10^{23} eV$ for neutrino mass consistent with the Super-Kamiokanda data which is clearly above the GZK cut off [6]. The difficulty in realizing this scenario is to identify the source of ultra high energy neutrinos with their energy close to the Z-resonance. Decay of a super heavy relic particle into neutrinos with mass $M_\chi \geq 10^{13} GeV$ has been proposed [6] to be the source of these highly energetic neutrinos that can explain cosmic ray events beyond the GZK cut off. Such neutrinos however, have to be produced in a spherical shell at the red shift $z = (\frac{M_\chi}{2E_{res}} - 1) = (\frac{M_\chi M_\nu}{M_Z{}^2} - 1)$ so that their energy near earth is close to the Z-resonance energy for the $\nu\bar{\nu}$ annihilation cross-section on the relic neutrinos to be large.If such fine tuning of mass of the relic super heavy particle or their abundance at the red shift $z = (\frac{M_X}{2E_{res}} - 1)$ is not available, we will require large neutrino hadron cross-sections of hadronic strength for the neutrinos to be able to initiate showers high in the atmosphere. Current estimates of the ultra high neutrino scattering in the Standard Model for $E_\nu \sim 10^{21} eV$ are estimated [7] to lie in the range $10^{-4} - 10^{-5} mb$. Specifically,

$$\sigma_{\nu N}{}^{SM}(E_\nu) \simeq (2\ -\ 3) \times 10^{-5} (\frac{E_\nu}{10^{19} eV})^{0.4} mb \tag{1}$$

The anomalously large high energy neutrino interaction requires new physics and an appealing possibility considered in the literature is the theory with n extra dimensions with large compactification radii and TeV scale quantum gravity [8]. In such theories, exchange of a tower of massive spin-2 bulk gravitons (Kaluza-Klein(KK) excitations) opens up the exciting possibility of extra contribution to any two particle scattering. In this context, the contribution of gravitational scattering to νN cross-section consistent with the requirement of unitarity has been estimated [9]. For example, for a neutrino of energy E_ν scattering on a proton at rest

$$\sigma_{\nu N}{}^{g}(E_\nu) \simeq \frac{4\pi s}{{M_s}^4} \simeq 0.1 (\frac{1TeV}{M_S})^4 (\frac{E_\nu}{10^{19} eV}) mb \tag{2}$$

The most stringent lower limits on the string scale M_S are obtained from astrophysical considerations [10] by studying the energy loss rates through the emission of bulk gravitons in SN 1987 A and lead to typically $M_S \geq 30$ Tev, 4 TeV and 1 TeV for the number of extra dimensions equal to 2, 3 and 4 respectively. Thus n=4 is required if neutrinos are to be the primary candidates for UHE cosmic ray events.

The new physics would open up new channels for these high energy neutrinos to annihilate with the relic neutrino background to produce bulk gravitons in the extra dimensions through

$$\nu\bar{\nu} \longrightarrow G_{KK} \tag{3}$$

and may therefore get effeciently attenuated during their intergalactic journey. In these theories, there also exists extra contributions to high energy neutrino scattering on relic background neutrinos through the exchange of KK excitations to produce the cascade of high energy particles through

$$\nu\bar{\nu} \longrightarrow f\bar{f} \tag{4}$$

and

$$\nu\bar{\nu} \longrightarrow \gamma\gamma \tag{5}$$

processes. In the Standard Model the process (4) takes place through the exchange of Z, while the process (5) can take place only through the loop diagrams and is expected to be highly suppressed [11]. In theories with extra dimensions, there is direct coupling between Standard Model particles and spin-2 gravitons, thus providing a unique channel.

Using the Feynman Rules given in [12], it is straight forward to calculate the above processes. The neutrino annihilation cross-section to produce bulk gravitons summed over all the KK states is calculated to be

$$\sigma(\nu\bar{\nu} \longrightarrow G_{KK}) = \frac{\pi^2}{s}(\frac{s}{M_s^2})^{\frac{n}{2}+1} \tag{6}$$

where n is the number of extra dimensions.

The scattering processes (4) and (5) can be calculated to get

$$\sigma^g(\nu\bar{\nu} \longrightarrow f\bar{f}) = \frac{\pi}{60s}(\frac{s}{{M_s}^2})^{n+2}\mathcal{F}^2 \tag{7}$$

and

$$\sigma^g(\nu\bar{\nu} \longrightarrow \gamma\gamma) = \frac{\pi}{20s}(\frac{s}{{M_s}^2})^{n+2}\mathcal{F}^2 \tag{8}$$

where $\mathcal{F}^2 = \pi^2 + 4I^2(\frac{M_s}{\sqrt{s}})$ and I is given in [12].

For a neutrino of energy E_ν annihilating a relic neutrino of mass m_ν, we get

$$\sigma^g(\nu\bar{\nu} \longrightarrow G_{KK}) \simeq 4 \times 10^{-33-\frac{3n}{2}} 2^{\frac{n}{2}} \left(\frac{m_\nu}{1eV}\right)^{\frac{n}{2}} \left(\frac{E_\nu}{10^{21}eV}\right)^{\frac{n}{2}} \left(\frac{1TeV}{M_s}\right)^{n+2} cm^2 \tag{9}$$

and

$$\sigma^g(\nu\bar{\nu} \longrightarrow f\bar{f}) \simeq 4 \times 10^{-38-3n} 2^n \left(\frac{m_\nu}{1eV}\right)^{n+1} \left(\frac{E_\nu}{10^{21}eV}\right)^{n+1} \left(\frac{1TeV}{M_s}\right)^{2n+4} \mathcal{F}^2 cm^2 \tag{10}$$

and

$$\sigma^g(\nu\bar{\nu} \longrightarrow \gamma\gamma) = 3\sigma^g(\nu\bar{\nu} \longrightarrow f\bar{f}) \tag{11}$$

to be compared with the Standard Model calculation

$$\sigma^{SM}(\nu\bar{\nu} \longrightarrow f\bar{f}) = \frac{G_F^2}{3\pi}\frac{M_Z^2 s}{(s - M_Z^2)^2 + M_Z^2\Gamma_z^2}(C_V^2 + C_A^2) \tag{12}$$

where ${C_V}^f = {T_3}^f - 2Q^f sin^2\theta_w$ and ${C_V}^f = {T_3}^f$. The Standard Model cross-section at $s = M_Z^2$ comes out to be $\simeq 1.59\times10^{-32}cm^2$. The process $\nu\bar{\nu} \longrightarrow \gamma\gamma$ has been recently calculatedin the Standard Model [13] and is given by

$$\sigma^{SM}(\nu\bar{\nu} \longrightarrow \gamma\gamma) = \frac{G_F^2\alpha^2}{640\pi^3}\frac{s^3}{M_w^4}A^2 \simeq 5.6 \times 10^{-42}\left(\frac{m_\nu}{1eV}\right)^3\left(\frac{E_\nu}{10^{21}eV}\right)^3 cm^2 \quad (13)$$

where A is taken to be $\simeq$14.4. The above expression is valid for $\sqrt{s}$ upto roughly $2M_w$ after which the cross-section reaches a plateau till about 1 TeV and then starts falling [13].

In Figures 1-3, we have plotted the cross-sections for the cases n = 2 and 4 with M_s = 1, 10 and 30 TeV. In Fig.4, we plot the cross-sectons for the parameters of the theory that are constrained from astrophysical considerations obtained by demanding that the supernova cooling through graviton production does not exceed 10^{53} ergs. We have also plotted the Standard Model cross-sections for $\nu\bar{\nu} \longrightarrow f\bar{f}$ and $\nu\bar{\nu} \longrightarrow \gamma\gamma$ for comparison. We see that the contribution of spin-2 graviton exchange for n=2 and M_s=1 TeV rises very fast with energy and far exceeds the Standard Model contribution. Such a large cross-section would result in the attenuation of high energy neutrinos if they are produced through the decayof a super heavy relic particle of mass M_χ exceeding 10^{14} GeV. The probability of these high energy neutrinos to interact depends upon the cross-section and on the lepton-asymmetry parameter $\eta = \frac{\eta_{\nu,relic}}{\eta_{\gamma,0}}$ whose value is constrained by nucleosynthesis and by large scale structure considerations. The mean free path of neutrinos is dominated by $\sigma(\nu\bar{\nu} \longrightarrow G_{KK})$ and is given by $\lambda = \frac{1}{\sigma(\nu\bar{\nu}\longrightarrow G_{KK})\eta_{\nu,relic}}$. If there is no lepton-asymmetry, $\eta\simeq0.14$ and could be as large as 4 for some cosmological parameters [14].For $\sqrt{s}$ = 500 GeV,the neutrino mean free path for n=2 and $M_s = 1TeV$ is $\lambda_{\nu\bar{\nu}\rightarrow G_{KK}}\simeq 0.57\times 10^7(\frac{0.14}{\eta})Mpc$ to be compared with the corresponding contribution in the Standard Model from the Z-exchange namely $\lambda_{\nu\bar{\nu}\rightarrow Z^*}{\simeq}1.33{\times}10^{10}(\frac{0.14}{\eta})Mpc$. For the astrophysically preffered value (n=4, $M_s = 1$ TeV), the mean free path is $\lambda_{\nu\bar{\nu}\rightarrow G_{KK}}{\simeq}2.27{\times}10^7(\frac{0.14}{\eta})Mpc$. At resonance, $\sqrt{s} = M_Z$, the Z-exchange gives by far the largest cross-section with mean free path $\lambda_{\nu\bar{\nu}\rightarrow Z^*res}{\simeq}0.345{\times}10^6(\frac{0.14}{\eta})Mpc$ to be compared with $\lambda_{\nu\bar{\nu}\rightarrow G_{KK}}{\simeq}6.8{\times}10^8(\frac{0.14}{\eta})Mpc$ for the astrophysically allowed parameters. However, neutrinos produced by the decay of super heavy relic particles with $\sqrt{s}{\geq}500GeV$ would mainly annihilate to produce bulk gravitons with a cross-section more than three orders of magnitude greater then the Standard Model cross-section through Z^* exchange. Thus, if neutrinos are to be the primary candidates for producing UHE cosmic rays, their interactions in theories with n extra dimensions with large compactification scale can be important and should be properly taken into consideration.

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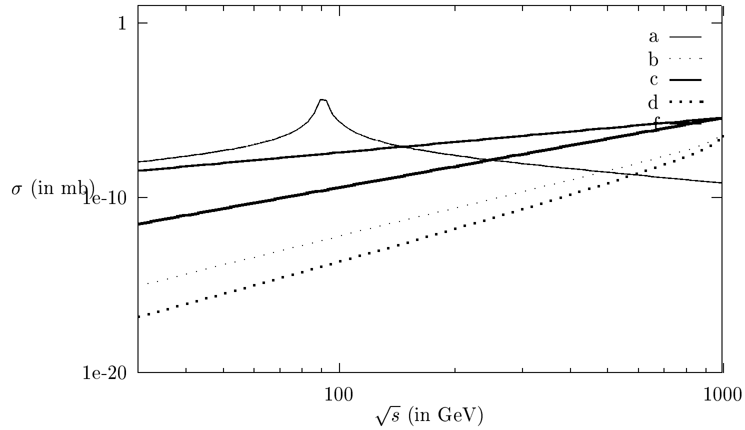

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Figure 1: Total $\nu\bar{\nu}$ annihilation cross-section as a function of $\sqrt{s}$. Curves a, b, c, d and f stand for $\sigma^{SM}(\nu\bar{\nu} \longrightarrow f\bar{f})$, $\sigma^{g}(\nu\bar{\nu} \longrightarrow f\bar{f}, n=2)$, $\sigma(\nu\bar{\nu} \longrightarrow G_{KK}, n=2)$, $\sigma^{g}(\nu\bar{\nu} \longrightarrow f\bar{f}, n=4)$, $\sigma(\nu\bar{\nu} \longrightarrow G_{KK}, n=4)$ respectively for $M_s = 1$ TeV.

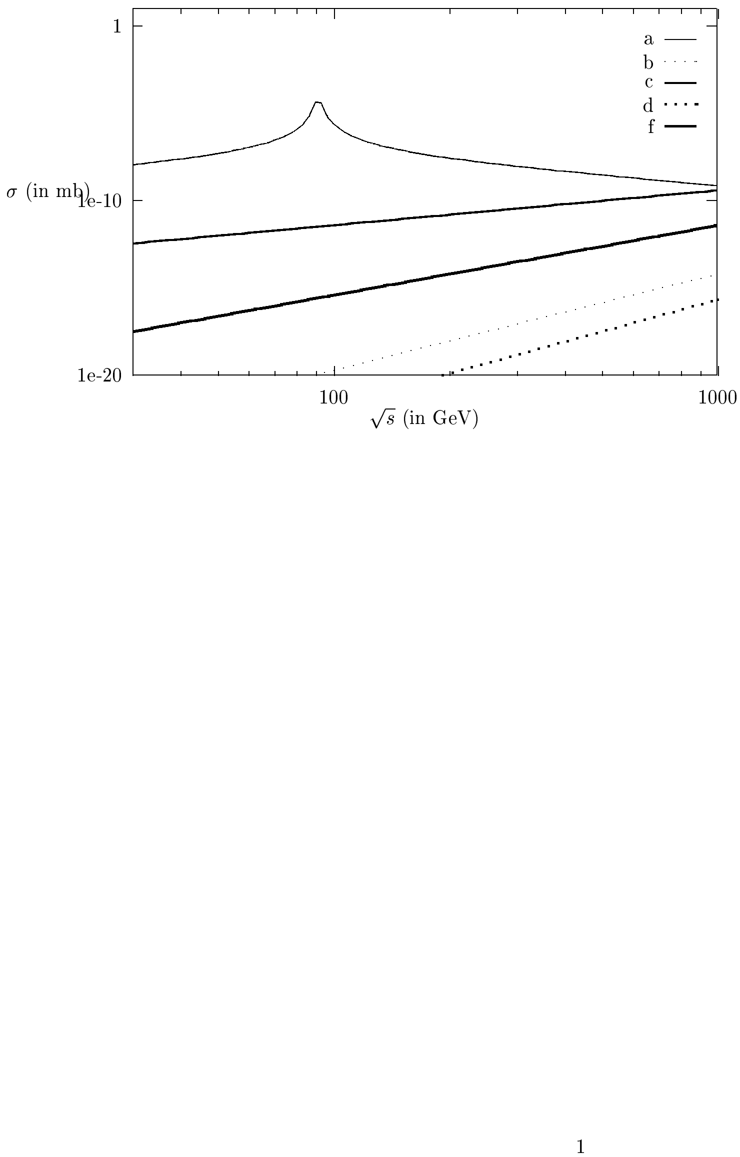

Figure 2: Total $\nu\bar{\nu}$ annihilation cross-section as a function of $\sqrt{s}$. The curves are as in Fig.1 and $M_s = 10$ TeV.

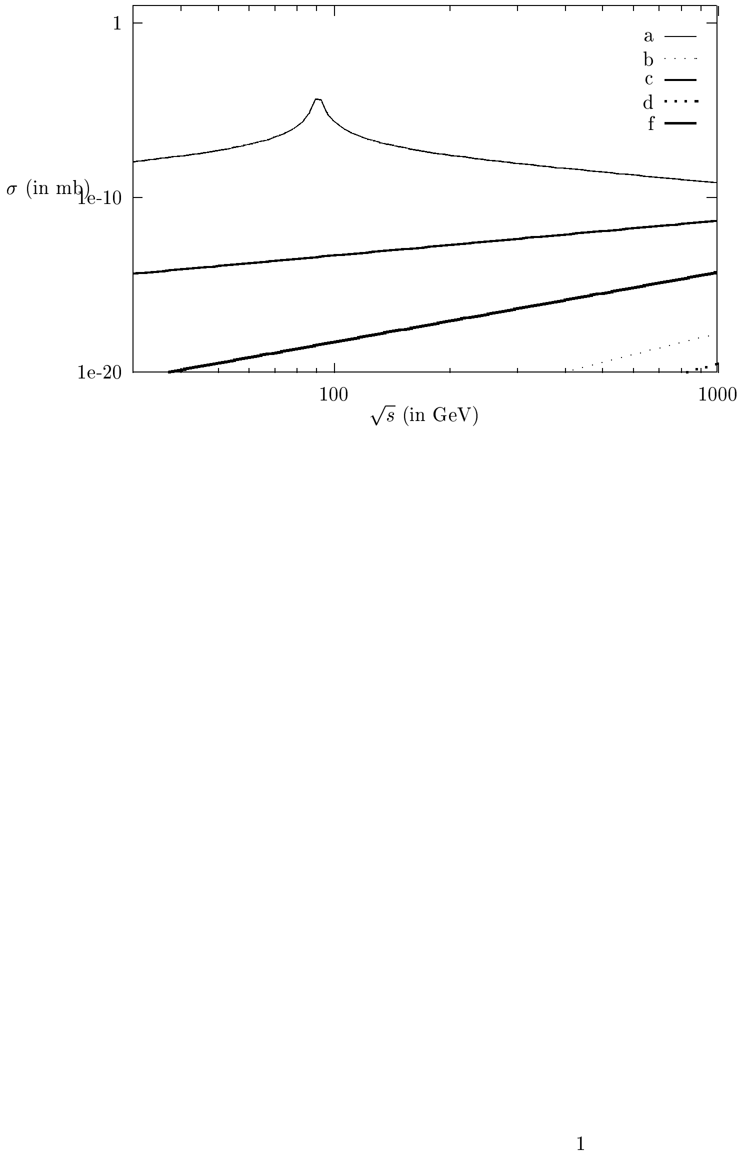

Figure 3: Total $\nu\bar{\nu}$ annihilation cross-section as a function of $\sqrt{s}$. The curves are as in Fig.1 and $M_s = 30$ TeV.

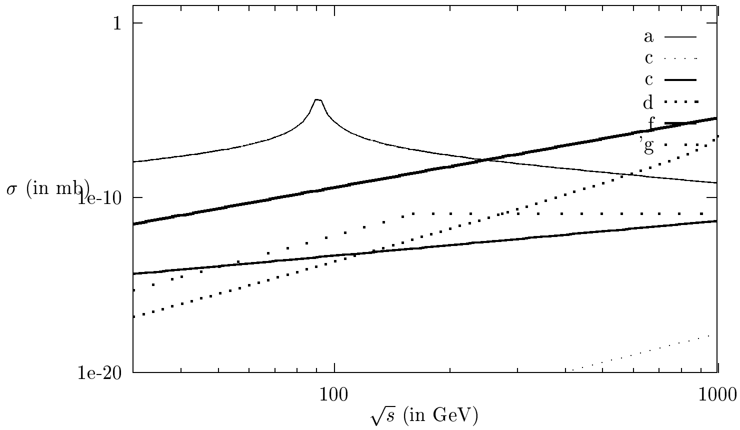

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Figure 4: Total $\nu\bar{\nu}$ annihilation cross-section as a function of $\sqrt{s}$ for the astrophysically costrained values of the parameters namely, M_s = 30 TeV for n = 2 and M_s = 1 TeV for n =4. Curves a, b, c, d and f are as in Fig.1. Curve g stands for $\sigma^{SM}(\nu\bar{\nu} \longrightarrow \gamma\gamma)$